AD-A147 453 LABORATORY INVESTIGATION ON ADHESIVES FOR NAVAL FACILITIES CONSTRUCTION(U) NAVAL CIVIL ENGINEERING LAB PORT HUENEME CA T NOVINSON MAY 84 NCEL-TN-1694 1/1

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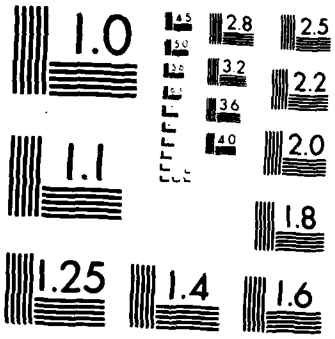


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TN NO: N-1694

AD-A147 453

TITLE: LABORATORY INVESTIGATION ON ADHESIVES FOR NAVAL FACILITIES CONSTRUCTION

AUTHOR: Thomas Novinson, Ph D

DATE: May 1984

SPONSOR: Naval Material Command and Marine Corps Headquarters

PROGRAM NO: ZF66.512.001.090
CF60.536.091.01.M42A

# TECHNICAL NOTE

NAVAL CIVIL ENGINEERING LABORATORY
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# METRIC CONVERSION FACTORS

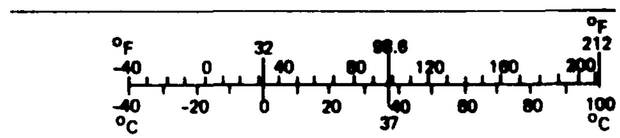
### Approximate Conversions to Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | *2.5 | centimeters | cm |
| ft | feet | 30 | centimeters | cm |
| yd | yards | 0.9 | meters | m |
| mi | miles | 1.6 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 6.5 | square centimeters | $cm^2$ |
| $ft^2$ | square feet | 0.09 | square meters | $m^2$ |
| $yd^2$ | square yards | 0.8 | square meters | $m^2$ |
| $mi^2$ | square miles | 2.6 | square kilometers | $km^2$ |
| | acres | 0.4 | hectares | ha |
| | | **MASS (weight)** | | |
| oz | ounces | 28 | grams | g |
| lb | pounds | 0.45 | kilograms | kg |
| | short tons (2,000 lb) | 0.9 | tonnes | t |
| | | **VOLUME** | | |
| tsp | teaspoons | 5 | milliliters | ml |
| Tbsp | tablespoons | 15 | milliliters | ml |
| fl oz | fluid ounces | 30 | milliliters | ml |
| c | cups | 0.24 | liters | l |
| pt | pints | 0.47 | liters | l |
| qt | quarts | 0.95 | liters | l |
| gal | gallons | 3.8 | liters | l |
| $ft^3$ | cubic feet | 0.03 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.76 | cubic meters | $m^3$ |
| | | **TEMPERATURE (exact)** | | |
| °F | Fahrenheit temperature | 5/9 (after subtracting 32) | Celsius temperature | °C |

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.


### Approximate Conversions from Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.04 | inches | in |
| cm | centimeters | 0.4 | inches | in |
| m | meters | 3.3 | feet | ft |
| m | meters | 1.1 | yards | yd |
| km | kilometers | 0.6 | miles | mi |
| | | **AREA** | | |
| $cm^2$ | square centimeters | 0.16 | square inches | $in^2$ |
| $m^2$ | square meters | 1.2 | square yards | $yd^2$ |
| $km^2$ | square kilometers | 0.4 | square miles | $mi^2$ |
| ha | hectares (10,000 $m^2$) | 2.5 | acres | |
| | | **MASS (weight)** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.2 | pounds | lb |
| t | tonnes (1,000 kg) | 1.1 | short tons | |
| | | **VOLUME** | | |
| ml | milliliters | 0.03 | fluid ounces | fl oz |
| l | liters | 2.1 | pints | pt |
| l | liters | 1.06 | quarts | qt |
| l | liters | 0.26 | gallons | gal |
| $m^3$ | cubic meters | 35 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.3 | cubic yards | $yd^3$ |
| | | **TEMPERATURE (exact)** | | |
| °C | Celsius temperature | 9/5 (then add 32) | Fahrenheit temperature | °F |



AD-A147453

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

| REPORT DOCUMENTATION PAGE | | READ INSTRUCTIONS BEFORE COMPLETING FORM |
|---|---|---|
| 1. REPORT NUMBER<br>TN-1694 | 2. GOVT ACCESSION NO.<br>DN187256 | 3. RECIPIENT'S CATALOG NUMBER |
| 4. TITLE (and Subtitle)<br>LABORATORY INVESTIGATION ON ADHESIVES FOR NAVAL FACILITIES CONSTRUCTION | | 5. TYPE OF REPORT & PERIOD COVERED<br>Final; Oct 1980 – Oct 1983<br>6. PERFORMING ORG. REPORT NUMBER |
| 7. AUTHOR(s)<br>Thomas Novinson, Ph D | | 8. CONTRACT OR GRANT NUMBER(s) |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS<br>NAVAL CIVIL ENGINEERING LABORATORY<br>Port Hueneme, CA 93043 | | 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS<br>62766N; ZF66.512.001.090, CF60.536.091.01M42A |
| 11. CONTROLLING OFFICE NAME AND ADDRESS<br>Naval Material Command<br>Washington, DC 20360 | | 12. REPORT DATE<br>May 1984<br>13. NUMBER OF PAGES<br>31 |
| 14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)<br>Marine Corps Headquarters<br>Washington, DC 20360 | | 15. SECURITY CLASS. (of this report)<br>Unclassified<br>15a. DECLASSIFICATION DOWNGRADING SCHEDULE |

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution is unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Adhesives, adhesive bonding strength, weathering, construction, testing

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report summarizes 3 years of laboratory findings on the comparative bonding strengths of adhesives to different construction materials and the effects of simulated weathering on adhesive bond strength. An adhesive used for construction should have a minimal tensile bond strength of 1,000 psi with the adherends being bonded. The selection of an adhesive should not be based on initial tensile strength alone because some adhesives may weaken upon prolonged exposure to hot and cold temperatures, oxygen, or seawater.

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20. Continued

The strongest adhesives tested for most nonporous construction materials were two-part epoxies, peroxide-cured polyesters, peroxide-cured acrylics, and two-part urethanes. Although no single adhesive is suitable for bonding every type of material, a definite trend in general strength of the five classes of adhesives was discovered: chemically reacting, one- or two-component adhesives (epoxies, polyesters, urethanes) are generally stronger than solvent-based or hot-melt adhesives, which are much stronger than most aqueous-based adhesives (casein, fish, glue, hide glue).

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LABORATORY INVESTIGATION ON ADHESIVES FOR NAVAL FACILITIES CONSTRUCTION
(Final) by Thomas Novinson, Ph D
TN-1694 31 pp illus May 1984 Unclassified

1. Adhesive bonding strength 2. Construction I. ZF66.512.001.090

This report summarizes 3 years of laboratory findings on the comparative bonding strengths of adhesives to different construction materials and the effects of simulated weathering on adhesive bond strength. An adhesive used for construction should have a minimal tensile bond strength of 1,000 psi with the adherends being bonded. The selection of an adhesive should not be based on initial tensile strength alone because some adhesives may weaken upon prolonged exposure to hot and cold temperatures, oxygen, smog, or seawater. The strongest adhesives tested for most nonporous construction materials were two-part epoxies, peroxide-cured polyesters, peroxide-cured acrylics, and two-part urethanes. Although no single adhesive is suitable for bonding every type of material, a definite trend in general strength of the five classes of adhesives was discovered: chemically reacting, one- or two-component adhesives (epoxies, polyesters, urethanes) are generally stronger than solvent-based or hot-melt adhesives, which are much stronger than most aqueous-based adhesives (casein, fish, glue, hide glue).

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## INTRODUCTION

The Navy spends millions of dollars each year to repair and maintain various structures (wood, concrete, or steel) damaged by weathering (sunlight, hot and cold temperatures, oxidation) or from simple wear-and-tear use. Modern structural adhesives can be used to patch, seal, or rebuild these damaged structures, thus extending their useful life. Adhesives can be used to install interior tiles, wallpaper, linoleum, carpets, etc. and exterior fascia, wood trim, multilayer roofs, etc. Epoxy adhesives, are indispensable in repairing cracked or spalled concrete.

Little information on adhesives is available in Naval Facilities Engineering Command (NAVFAC) documents (Ref 1), and the Office of Naval Research has actively encouraged research and development (R&D) in adhesives technology (Ref 2). In order to make more practical information on structural adhesives available to Navy users, the Naval Civil Engineering Laboratory (NCEL) initiated an Independent Exploratory Development (IED) study of selected commercial adhesives. This investigation was designed to provide comparative strengths and short-term durability data of various commercially available adhesives for use by Navy shore activities in construction or repair. There were plans to transition the study from the laboratory to field testing and evaluation, but these plans were postponed due to funding problems. This report summarizes 3 years of laboratory findings on the comparative bonding strengths of adhesives to representative construction materials (steel, wood, concrete, and others) and the effects of simulated weathering on adhesive bond strength. Although the work was limited to laboratory testing, the results on bond strength should provide some guidance to field personnel on the selection of various adhesives or sealants for specific field applications until the time that field tests can be conducted.

## APPROACH

There are more than 10,000 adhesives marketed today (Ref 3). Selecting the best adhesive (e.g., the strongest, most durable, etc.) for a given set of materials to be bonded (adherends) is a difficult task for those unfamiliar with the technology. Although there are many excellent books and articles on specific adhesives, much of the information is not readily usable for Naval construction or maintenance activities. Military and Federal specifications normally describe initial tensile strengths only and rarely mention the generic or chemical class of the adhesive. Commercial sales literature, although often detailed, is oriented toward the vendor's products, with little or no comparative data on other related adhesives.

NCEL could not possibly test all 10,000 adhesives, but the following approach was used in the study:

1. Classify commercially available adhesives in 5 or 6 smaller groups based on individual chemical or physical properties (described in Ref 4 and 5).

2. Select 6 to 12 adhesives from each of these classes for testing.

3. Select or develop uniform tests to determine comparative adhesive strength, regardless of the type of adhesive or nature of the adherend.

4. Determine adhesive strength differences between individual adhesives and different adherends (metal, wood, concrete, etc.).

5. Determine adhesive strengths for various adhesive types (epoxy, polyester, urethane, etc.) with single sets of adherends (aluminum, steel, concrete, etc.).

6. Determine any increase or decrease in adhesive strength for selected adhesives (e.g., epoxies) and selected adherends (e.g., steel or aluminum) exposed to (1) ocean water; (2) high humidity and heat; (3) oxygen or oxidizing atmosphere (i.e., smog); (4) dry heat; and (e) severe cold.

7. Prepare bar charts that provide comparative strengths of available adhesives bonded to different adherends. Also provide short-term durability information for a number of adhesives exposed to simulated climatic extremes.

## CLASSIFICATION OF ADHESIVES

### General

The thousands of commercially available adhesives can be subdivided into five classes for easy reference and discussion. Classification is based on chemical or physical characteristics, chemical composition, or reactivity. Generic names are assigned on the basis of the principal resin present (epoxy, urethane, vinyl, resorcinol, etc.) because the mechanism of curing and bond strength development are functions of the resin. However, it should be noted that adhesives are complex mixtures including not only the resin but also plasticizers, tackifiers, ultraviolet (UV) absorbants, antioxidants, etc. that can affect the properties of the products.

The five classes of adhesives are:

1. Water-emulsion adhesives: casein, vegetable, acrylics, polyvinyl alcohol, fish glues, hide glues, and other plant or animal products.

2. Organic-solvent-based adhesives: neoprene, silicone, polysulfide, acrylics, etc. in toluene, xylene, or other solvents with added modifiers (as discussed above).

3. Hot melts: thermoplastic copolymers that are melted and applied to adherend surfaces; when the liquid resolidifies, the bond is formed.

4. One-component, solvent-free liquids: cyanoacrylates, such as "Super Glue"; anaerobics used for tightening bolts and screws by exclusion of air.

5. Two-component, solvent-free liquids (also gels and pastes): epoxies, urethanes, polyesters, peroxide-catalyzed acrylics, etc.

In this study, most of the adhesives tested were chosen from classes 1, 2, 4, and 5. Hot-melt adhesives (class 3) were not included because their strengths are similar to many of those of the solvent-based adhesives in class 2 (Ref 4).

## Epoxies

Although epoxy adhesives are in class 5, they almost constitute another class by themselves because there are so many variations and combinations of resin and curing agent. There are at least 64 different commercially available epoxide resin bases (part A) and 65 different curing agents (part B), thus allowing for more than 4,000 possible combinations. The unreacted resins are epoxides (strained cyclic ethers) of aromatic phenols. The major curing agents are (Ref 6):

1. polyamides

2. polyamines (aromatic and aliphatic amines)

3. polysulfides

4. certain acid anhydrides

The curing agents or hardeners vary in viscosity, color, and odor. The colors may range from water-white to yellow to brown to black, which gives a variety of different shades of cured epoxies from clear, colorless films to dark gray materials. The cured epoxies vary widely in strength, compatibility with different adherends (e.g., some have great affinity for metals but not for plastics or wood), and heat or chemical resistance.

A complete treatment of the epoxies is beyond the scope of this report, but all of the epoxies listed in Table 1 have different (proprietary) curing agents and would thus be expected to exhibit widely differing properties. Unfortunately, none of the manufacturers would identify the curing agents used in their epoxy formulations. NCEL was unable to analyze these chemicals using infrared spectroscopy, primarily because hydrogen bonding from the $NH_2$ group of amines and polyamides tends to obscure other important infrared bands.

## SELECTION OF TEST METHODS

### Bonding Strength

The tests described by the American Society for Testing and Materials (ASTM) for adhesive strength are generally specific and narrow in scope. NCEL desired more basic adhesive strength test methods applicable to a wide variety of adhesives used in bonding a variety of different structural materials. For these tests, a tensile or shear strength of 1,000 psi was arbitrarily selected as the minimum test strength.

There are four basic types of tests that are used for adhesive strength: (1) tensile, (2) shear, (3) torsion, and (4) peel (Figure 1). Because torsion testing requires a uniform rolling action, it was considered to be too complex for the instrumentation at hand. Peel testing was limited because other research groups have determined that most adhesives have peel strengths in the range of 5 to 10 psi, even if their tensile and shear strengths are 2,000 psi or higher (Ref 7). Therefore, the two tests chosen for these studies were (1) a modified version of an ASTM tensile test, and (2) an NCEL-developed, double-lap compressive shear test.

The tensile test used at NCEL is a modification of ASTM method D897 (tensile properties of adhesive bonds), as shown in Figure 2. The flat end of a dumbbell-shaped probe of the stiffest member of the adherend pair (e.g., metal) is coated with adhesive and then pressed against a flat sheet or block of the other adherend (e.g., wood, concrete, glass, etc.). Excess adhesive is removed. After the adhesive has fully cured, the probe is pulled away vertically on an tensile testing machine (Instron or similar) until the bond ruptures. The load (kg or lb) is divided by the surface area of contact ($cm^2$ or $in.^2$) to yield tensile bond strengths in $kg/cm^2$ or psi.

The shear test developed by NCEL is a modification of ASTM method D2718 (rolling shear adhesion). Two methods were considered at first. In the double-lap tensile shear test (Figure 3), the jaws of a tensile testing machine are clamped to the center plate of a three-piece "sandwich" (center plate bonded between two outer plates), and then the center plate is pulled out vertically. In the double-lap compressive shear test (Figure 4), the platen of a tensile-compression testing machine is used to push the center plate down. After several experiments, it was decided that the compressive shear test was easier to perform, more reproducible, and required less elaborate equipment than the tensile shear method.

The tensile test (Figure 2) was used on all the samples tested (adhesive with each pair of adherends), and the double-lap compressive shear test (Figure 4) was performed on approximately 25% of these. The tensile and compressive shear tests were then compared in bar charts to illustrate the relative strengths of adhesives tested two different ways (see Appendix).

## Environmental Weathering

The Navy and Marine Corps have bases located throughout the world in a wide variety of climates. Adhesives, which are chiefly composed of organic chemicals, may deteriorate in severe climates (hot, cold, humid, oxidative, etc.) or from prolonged exposure to seawater or salt spray. Since it was of interest to determine the effects of environment on long term strength, NCEL also investigated the effects of laboratory-simulated weathering on the adhesives selected in this report.

Laboratory tests were developed to simulate field exposure. Microenvironments were set up in glass and plastic bell jars to simulate (1) submersion in the ocean, (2) exposure to tropical heat, (3) oxidation (by ozone or other oxidants in the air), (4) desert heat, and (5) polar freezing. Some of the samples tested for initial tensile strength were placed in the chambers and exposed to these microenvironments for up to 5 weeks (the length of time available to conduct this study). Samples were periodically withdrawn (1, 3, and 5 weeks) and tested for tensile strength. The results were plotted as tensile strength versus time of exposure (see Appendix), and then analyzed for trends (i.e., decrease, increase, or no change) in bond strength.

## Surface Preparation

For effective bonding, the adhesive must thoroughly wet the surface of the substrates (i.e., there must be no grease, oils, dirt, water, or air pockets between the adherend and adhesive). To satisfy these conditions, the adherends must be clean, dry, and reasonably smooth. Some specialty adhesives, such as the cyanoacrylates (Eastman 910 or Superglue), require a basic surface to catalyze the formation of adhesive bonding. Anaerobic adhesives require the exclusion of air before they polymerize and form the adhesive bond. The subject of surface preparation is quite complex and is covered in depth elsewhere (Ref 3), but some of these methods were used in the present work and are summarized below:

<u>Steel</u>: Cleaned with diluted sulfuric acid (concentrated acid diluted 1:10 with water) and rinsed with water or sand blasted to white metal.

<u>Aluminum</u>: Cleaned with chromic acid (10 parts concentrated sulfuric acid and 4 parts sodium dichromate) for 5 minutes at 70°F, then rinsed with water.

<u>Brass</u>: Cleaned with chromic acid for 10 minutes at 70°F, then rinsed with water, then rinsed with concentrated ammonium hydroxide and rinsed with cold water.

<u>Titanium</u>: Cleaned with 70% nitric acid for 10 minutes at 70°F, then rinsed with cold water.

<u>Concrete</u>: Degreased with aqueous, alkaline detergent, such as Alconox, then rinsed with water and air dried.

Glass: Cleaned and degreased with 10% trisodium phosphate in water at 100°F for 20 minutes, then rinsed with cold water, then rinsed with acetone and air dried.

Wood: Sanded to remove 1 mm of the surface (if the wood is greasy, it may also be degreased with methylene chloride or chloroform and air dried).

## Joint Design

Joint design is very important in creating the strongest bonds. End-to-end bonds are the weakest, followed by single overlap (single lap) and double overlap (double lap). If possible, metals, wood, and plastics can be machined to provide "staircase" or jagged interlocking surfaces or dovetail joints for the greatest strength (Ref 3):

bond strength increases as

end-to-end << single lap < double lap < dovetail or staircase

The joints described in the test procedure were simple end-to-end or lap joints due to the requirements of the test procedures.

## Static Versus Dynamic Loading

All the tests performed in this work were on samples with no stress or strain placed on the joint (static). Tensile tests performed on joints exposed to dynamic loading would be of interest because this would more closely resemble many real life uses of construction adhesives. Dynamic loading was not performed in this work unit, however, because it involves a great number of variables and would require many years to develop the test data. In future work, NCEL should study some of the same adhesives investigated in this paper, under both static and dynamic loading.

# TEST PROCEDURE

## Tensile Tests

The more durable materials (e.g., wood, metal, plastic) were machined into rods, and then the center was ground out to form a "dumbbell" shape with ridges to support the clamps on the tensile testing machine. Each dumbbell (or probe) was 9 cm long with a radius of 0.564 ±0.0005 cm. The center 4 cm were cut to a diameter of about 0.8 cm (Figure 2). The 1-$cm^2$ area of the probe ends permitted easy calculation of the adhesive strength in $kg/cm^2$ from the load (kg) at failure.

The probe ends were bonded to 10- by 6- by 0.5-cm plates of various substrates (e.g., wood, steel, aluminum, glass, concrete, and plastic). The concrete plates were generally about 30 cm thick because the minimum diameter of the aggregate was about 20 cm. A precise amount of each adhesive was used to bond the probe to the plate so that little or no liquid was squeezed out at the glue line. When there was excessive adhesive, it was allowed to harden and then was removed by cutting around the edges of the probe with a razor blade. This ensured that exactly 1 $cm^2$ of surface area was bonded.

The probes were pulled off the plates at a constant rate using a tensile testing machine, and the loads at which failure occurred were recorded. Both metric units ($kg/cm^3$) and English units ($lb/in.^2$ or psi) were used in the data treatment.

## Double-Lap Compressive Shear Tests

A sandwich or laminated composite was made from three plates and the adhesive. The assembly was clamped into place, and the middle plate was pushed down in compression. As in the other test method, adhesive strength was reported in both metric ($kg/cm^2$) and English (psi) units.

## Environmental Tests

Seawater Immersion. Samples were immersed in fresh, circulating filtered seawater maintained at 70 ±2°F in a large glass tank. The seawater was changed when rust or other debris was seen.

Oxidation. Samples were placed in a 10-liter plastic bell jar (with cover) fitted with inlet and exit tubes for oxygen. Oxygen was purged through the system at atmospheric pressure, and the temperature (70 ±2°F) and relative humidity (50 ±2%) were monitored with gages.

Heat and Humidity. Samples were placed in a 10-liter plastic bell jar (with cover) and were heated to 90°F with insulated electrical tape connected to a variable resistor heater. The relative humidity of 98 ±1% was maintained by placing a beaker (100 ml) of saturated zinc chloride (aqueous) solution under the bell jar.

Dry Heat. Probes glued to plates were placed in a standard laboratory oven set at 104°F. The relative humidity (which was not controlled) was measured at 30 ±5% over the 5-week period of the test.

Cold Temperatures. Samples were placed in a freezer. The temperature was checked daily and gave an average reading of -14 ±2°F. The relative humidity was also checked daily with a standard temperature-humidity gage and was recorded as 20 ±2%.

## Statistical Treatment of the Data

Each tensile test was run in triplicate. When the values were within acceptable reproducibility (e.g., 1,000 ± 50 psi as opposed to 1,000 ± 200 psi), the average strength and the standard deviation were recorded. When the three test values varied significantly (e.g., 1,000 ± 200 psi), three to five additional tests were performed, and the total data were used to calculate a mean and a statistical variance using the Poisson distribution, a chi-test, and other statistical methods (Ref 8).

## TEST RESULTS

All the adhesives studied are listed in Table 1, along with the codes assigned by NCEL, their generic names, and the adhesive class. The codes were used as abbreviations for the longer tradenames in the various bar graphs and charts.

### Tensile Strength

The tensile strength tests were much more reproducible than the shear tests conducted. The reason might be that the surface area of contact for the tensile specimens was smaller and, therefore, adhesive could be applied in a more uniform, controlled layer.

Steel-to-Steel. Of the 35 adhesives tested, only 8 met the 1,000-psi structural requirement: 5 two-part epoxies, 2 urethanes, and 1 peroxide-cured polyester (see Figure 5). Tracon Trabond 2114 (epoxy FF), at 3,770 psi, had the highest tensile strength. The two Hardman Kalex urethanes, Hi-Peel (O) and Semi-Peel (P), had fairly high tensile strengths of 1,896 and 2,245 psi, respectively. Duro-E-Pox-E (G), an epoxy/polyamide, and Reziweld 1000 (BB), another two-part epoxy, also were fairly high at 1,700 and 1,835 psi, respectively. Two other epoxies, Hardman Epoxy (M) and Tracon Trabond 2101 (DD), had tensile strengths of 1,035 and 1,080 psi, respectively, which were slightly over the minimum requirement. The peroxide-cured polyester, Daubond Bondo (F), just met the structural requirement with a tensile strength of 1,000 psi.

Wood-to-Wood. No adhesives had strengths of 1,000-psi with wood bonded to wood (see Figure 6). The maximum tensile strength was 570 psi (Tracon Trabond 2143D (KK), a two-part epoxy). The reason for these generally lower tensile strengths is that wood is weaker (lower Young's modulus) than steel and concrete and is much more porous than steel, so it would be expected that some of the adhesive is absorbed by the substrate material to account for the lower bond strengths.

Aluminum-to-Aluminum. Several adhesives performed well in bonding aluminum, which is generally more difficult to bond than steel (probably because aluminum forms a tenacious coating of aluminum oxide that is difficult to remove). The acrylics K, V, and W had the highest tensile strengths of 2,960, 2,700, and 2,690 psi, respectively. Hardman Kalex Semi-Peel urethane (P) again performed satisfactorily at 1,170 psi. Of the six epoxies that met the requirement, Reziweld 1000 (BB), at 2,490 psi, was the most notable. Figure 7 presents a bar chart of the 25 different adhesives tested.

Brass-to-Brass. Of the 11 different adhesives tested, only 3 met the 1,000-psi structural requirement (see Figure 8). The top performer was Hardman Acrylic (K) at 3,295 psi. Hardman Kalex Semi-Peel urethane (P) continued to perform well at 1,765 psi. Hardman Extra Fast Setting Epoxy (L), which failed to meet the requirement with the other substrates, had a tensile strength of 1,140 psi.

Other Substrates. Figures 9 through 15 show the results of tensile tests using different combinations of substrates. Out of 43 different combinations only 3 adhesives met the 1,000-psi structural requirement. Hughson-Lord Versilok #4 (V), a peroxide-cured acrylic, did well on steel-to-glass and aluminum-to-glass substrates at 1,270 and 1,165 psi, respectively. Reziweld 1000 (BB), an epoxy, had a tensile strength of 1,305 psi on steel-to-glass substrates.

### Compressive Shear Strength

Because it was difficult to get a statistical mean with a small standard deviation, the double-lap compressive shear test was aborted. The results of the tests that were performed are as follows.

Steel-to-Steel. Of the 18 adhesives tested, only 3 met the 1,000-psi structural requirement, and all were epoxies (see Figure 5). Reziweld 1000 (BB) performed the best at 2,175 psi; Tracon Trabond 2114 (FF) and Tracon Trabond 2135D (JJ) followed with 1,850 and 1,150 psi, respectively.

Wood-to-Wood. No adhesives met the arbitrary 1,000-psi minimum (see Figure 6), but the maximum bond strength appeared to be around 500 psi for the better wood adhesives. The best adhesives (over 500 psi tensile) were Hardman Kalex semi-peel urethane (P), Hardman regular set epoxy (Q), and Tracon Trabond 21430 epoxy (KK).

Aluminum-to-Aluminum. Five adhesives met the 1,000-psi structural requirement: two two-part epoxies and three peroxide-cured acrylics (see Figure 7). Of the epoxies, Tracon Trabond 2114 (FF) had the highest compressive shear strength at 2,680 psi, followed by Reziweld 1000 (BB) at 1,590 psi. Of the acrylics, Hughson-Lord Versilok #5 (W) had the highest compressive shear strength at 2,000 psi, followed by Hughson-Lord Versilok #4 (V) and Hughson-Lord Versilok #17 (X) at 1,920 and 1,550 psi, respectively.

Other Substrates. Figures 9, 10, and 12 show the results of the compressive shear tests using different combinations of substrates. The same three adhesives that met the structural requirement in the tensile tests also met the requirement in the compressive shear tests: Hughson-Lord Versilok #4 (V) at 1,000 psi on both steel-to-glass and aluminum-to-glass substrates, and Reziweld 1000 (BB) at 1,250 psi on steel-to-glass substrates.

### Simulated Weathering Tests

Graphs are plotted for tensile strength (psi) versus weeks of exposure (0 to 5 weeks) for several representative adhesives bonding either steel-to-steel or aluminum-to-aluminum exposed to a number of simulated weathering conditions (seawater immersion, oxidation, high humidity, dry heat, and cold).

Seawater Immersion. In Figure 16a, the results of immersing bonded steel joints in seawater for 5 weeks are shown. Epoxy HH, resorcinol NN, and methacrylic PP adhesives showed little, if any, change in strength, but epoxy GG apparently increased in strength, possibly due to continued curing over the 5-week period.

In Figure 16b, the results for aluminum were also somewhat unusual. In two cases, the adhesive appeared to lose strength (anaerobic acrylic Z and epoxy II), while in two others the strengths actually increased (epoxy FF and epoxy HH). The reason for the increase in strength is unknown.

Oxidation. For bonded steel joints, exposure to oxygen caused strength reductions in epoxies FF and DD, increases with epoxies EE and GG, and little or no change with methacrylic PP adhesive (Figure 17a). Once again, the reasons for the increase in strengths are unknown, but could be due to additional curing with time, which is unrelated to the presence of oxygen.

For the aluminum joints, epoxies EE, FF, and GG lost strength when exposed to oxygen for 5 weeks (Figure 17b). Epoxy HH exhibited very unusual behavior in that the strength appeared to decrease by 3 weeks and then increase by the end of 5 weeks. The high strength seen at 5 weeks could be an artifact, however.

High Heat and Humidity. In Figure 18a, the effects of high humidity (98%) and heat (90°F) on several steel-to-steel specimens bonded with epoxies, a resorcinol, and a methacrylic adhesive are shown. Heat and humidity appeared to have a pronounced deteriorative effect on epoxy FF, little or no effect on epoxy DD, and a slight effect on resorcinol MM; however, some increase was seen in the strength of methacrylic PP.

For aluminum specimens (Figure 18b), heat and humidity were beneficial for epoxies DD and EE and for anaerobic acrylic Z, but a substantial decrease in strength was shown by acrylic W. The reason for the increase in strength in the three adhesives was not investigated, but it could be due to continuous curing or cross-linking of the resin over a 5-week period.

Dry Heat. For the steel specimens, dry heat (104°F) caused a marked deterioration of epoxy FF, as shown in Figure 19a. Heat had little or no effect on nitrocellulose adhesive B and resorcinol NN, but it appeared to increase the strength of methacrylic PP and epoxies GG and HH.

For the aluminum specimens (Figure 19b), heat caused some deterioration in anaerobic acrylic Z and epoxy FF, but resulted in increased strength in epoxies GG and HH.

Cold Temperatures. As shown in Figure 20a for steel specimens, slight increases in strength were seen with resorcinol MM and epoxy EE exposed to cold. Epoxies FF and HH had remarkable increases in strength, while epoxy DD lost strength.

For aluminum specimens (Figure 20b), cold temperatures had some deteriorative effects on anaerobic acrylic Z and epoxies GG and DD, while causing some slight increase in strength in epoxies FF and HH.

## DISCUSSION

The 42 adhesives investigated represent four of the five classes discussed earlier (all but the hot melts) and cover a wide variety of resin bases available commercially, including:

- epoxies
- polyester
- urethane
- neoprene rubber
- nitrile rubber
- silicones
- reclaimed rubber
- polysulfide
- protein
- methacrylic
- nitrocellulose
- natural rubber
- resorcinol
- polyvinyl chloride (PVC)
- anaerobic acrylic

Figures 5 through 15 lists initial comparative tensile and compressive shear strengths of selected adhesives with different sets of adherends (e.g., steel, aluminum, brass, concrete, titanium, wood, etc.). By carefully comparing the charts and selecting the highest bar for a particular set of materials, the Navy user, with no prior knowledge of the adhesives field, should be able to select an appropriate adhesive for a particular use. By using the generic name (e.g., polyester, urethane, etc.), the user can excercise judgment in the selection of a suitable adhesive to bond two different materials (or the same material to itself).

The information on simulated weathering in the laboratory may also be of some use, since it gives the user some idea of the trend of adhesive strength for up to 5 weeks of exposure. With these data, the user will be able to predict whether specific adhesives used with specific adherends in the environments described retain or lose their bond strength over at least a 5-week period.

Epoxy adhesives vary widely in strength. The same epoxy formulation, in fact, may bond strongly with plastics and weakly with another material, or vice versa. It is impossible to predict these differences and each individual epoxy should be tested with the substrates intended for use.

The selection of an adhesive should not be based on initial tensile strength alone because some adhesives may weaken upon prolonged exposure to the environment. The user should ask the adhesive supplier to provide data on any decrease of strength with time of exposure for the particular adhesive of interest.

It should be clear that many adhesives are excellent for bonding one type of material (e.g., steel to steel) but are poor for bonding others (e.g., plastic to plastic). No single adhesive is suitable for bonding every type of material. However, there definitely is a trend in general strength of the five classes of adhesives:

class 5   class 4 > class 3 ≈ class 2 >> class 1

Thus, chemically reacting adhesives (epoxies, polyesters, urethanes) are generally stronger than solvent-based (or hot-melt) adhesives, which are much stronger than most aqueous-emulsion adhesives (casein, fish, glue, hide glue).

## CONCLUSIONS

1. The NCEL tensile test provides reproducible results, if used properly, e.g., the surfaces of the adherends are clean and dry and excess adhesive is not used.

2. The NCEL double-lap compressive shear test is much less reproducible than the tensile test.

3. The weakest adhesives are the water-based emulsions, followed by the organic solvent-based solutions of polymers.

4. The strongest adhesives (highest tensile strength) for most nonporous construction materials are the solvent-free, chemically curing epoxies, peroxide-cured polyesters, peroxide-cured acrylics, and urethanes.

5. Epoxies vary widely in their strength with different adherends.

6. Adhesive strength may increase, decrease, or remain the same depending upon environmental factors and, therefore, initial adhesion is not a true indicator of strength.

7. No single adhesive is suitable for bonding every type of material. However, there is a definite trend in general strength of the five classes of adhesives. Chemically reacting, adhesives are generally stronger than solvent-based or hot-melt adhesives, which are much stronger than most aqueous-based adhesives.

8. Most adhesives bond steel to steel stronger than aluminum to aluminum or titanium to metals. This may be due to surface chemistry (type of oxide film) differences.

9. Few adhesives yield bond strengths above 500 psi for bonding wood to wood. This may be due to the porosity of wood, which tends to absorb the adhesive before curing is complete.

## RECOMMENDATIONS

### Current Applications

The NCEL recommendations for adhesives to bond steel, aluminum, and other materials are summarized in Table 2 (which is a condensation of the graphical material presented in Figures 1 through 15). It should be noted that these recommendations are based on end-to-end tensile tests under static loading with samples cleaned as described in the Surface Preparation section. It should be cautioned, however, that results might be appreciably different for adherends using double-lap or dovetail joints, contaminated surfaces, or exposure to the stress and strain of dynamic loading. Results might also be different for adhesive-bonded joints exposed to rain, snow, desert or tropical heat and sunshine, urban smog, or other natural environments.

## Future Field Testing

Originally, there were plans to transition this work unit from laboratory testing in simulated environments to field testing under actual environments. This work should still be performed at some future date to determine whether field performance of the high strength adhesives parallel the laboratory strength studies. If the strengths are comparable, most new adhesives can be screened in the laboratory at minimal expense, and recommendations for field use can then be made. Examples of such testing would be bonding several wood-to-wood, steel-to-steel, plastic-to-plastic (PVC, acrylic, polyester, and other types), and concrete-to-concrete specimens with selected high-strength adhesives and placing these specimens in different climatic extremes (polar, cold and wet, cold and dry, moderate temperature, hot and dry, hot and humid, and smoggy heat). Some specimens would periodically (once a month) be withdrawn and tested for tensile strength at NCEL. The data would be plotted on curves of strength (psi) versus time of exposure (months), as in Figures 16 to 20. Testing would be performed for 12 to 36 months to obtain sufficient data for long-term weather exposure studies.

## Future Laboratory Studies

Future laboratory work should focus on retesting the bonded joints (wood-to-wood, metal-to-metal, and other combinations) under both static and dynamic loads using the new Instron tensile testing machine recently purchased by NCEL. Work is also recommended to determine the tensile strength and surface properties (adhesion compatibility, surface tension, wetting of the substrate) of epoxies formed by treating the glycidyl ethers of bis phenol A (Shell Co. "Epon" series used in the most epoxy formulations) with different curing agents, such as polysulfides, amines, acid anhydrides, polyamides, and polyimides.

## Benefits

The major benefit of both the present (and future proposed) studies is that comparative data on a wide variety of generic (chemical name) adhesives are now available for different substrates (wood, steel, concrete, aluminum) of interest to the Naval Shore Establishment. Detailed chemical composition studies correlated with strength and laboratory testing correlated with field testing (for strength under stress and prolonged environmental exposure) can be used to write more useful performance specifications for adhesives than are presently available (e.g., military and Federal). The importance of better adhesive specifications will become evident as state building codes change to allow greater use of structural adhesives. The Naval Shore Establishment will benefit by replacing corrodable metal fasteners with chemically resistant adhesives, thus reducing maintenance costs due to corrosion.


# ACKNOWLEDGMENTS

The author would like to thank technicians Ms. Nathalie Milliken and Mrs. Gina Melendez for their assistance in performing the tests on the adhesives.

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Table 1. List of Adhesives Studied

| Adhesive | Generic Name | Class[a] | NCEL Code |
|---|---|---|---|
| Allen Seal-All | polyvinyl chloride | 2 | A |
| Ambroid Liquid Cement | nitrocellulose | 2 | B |
| B.F. Goodrich | reclaimed rubber | 2 | C |
| Campbell-Odell | polysulfide | 2 | D |
| Carboline | neoprene | 2 | E |
| Daubond Bondo | polyester/benzoyl peroxide cured | 5 | F |
| Duro E-Pox-E | epoxy/polyamide | 5 | G |
| Duroplastic | rubber cement | 2 | H |
| GC Electronic | acrylic | 2 | I |
| Goodyear Pliobond | nitrile rubber | 2 | J |
| Hardman "Acrylic" | acrylic | | K |
| Hardman Extra Fast Setting Epoxy | epoxy/unspecified curing agent | 5 | L |
| Hardman Fast Setting Epoxy | epoxy/unspecified curing agent | 5 | M |
| Hardman "General Purpose Epoxy" | epoxy/unspecified curing agent | 5 | N |
| Hardman Kalex Hi-Peel | urethane | 5 | O |
| Hardman Kalex Semi-Peel | urethane | 5 | P |
| Hardman Regular Set | epoxy/polyamine | 5 | Q |
| Hardman "Silicone" | silicone | 2 | R |
| Hardman "Very Flexible" | epoxy/polyamine | 5 | S |
| Hardman "Water Clear Epoxy" | epoxy/unspecified curing agent | 5 | T |
| Hardman "Wet Surface Patching" | epoxy/unspecified curing agent | 5 | U |
| Hughson-Lord "Versilok" #4 | acrylic/peroxide-cured | 5 | V |
| Hughson-Lord "Versilok" #5 | acrylic/peroxide-cured | 5 | W |
| Hughson-Lord "Versilok" #17 | acrylic/peroxide-cured | 5 | X |
| Koppers Penacolite #4422 | acrylic | 2 | Y |
| Loctite "Superbond" | anaerobic acrylic | 4 | Z |
| Nicholson Hide Glue | protein | 1 | AA |
| Reziweld 1000 | epoxy/unspecified curing agent | 5 | BB |
| Stabond | neoprene | 2 | CC |
| Tracon "Trabond 2101" | epoxy/unspecified curing agent | 5 | DD |
| Tracon "Trabond 2106T" | epoxy/unspecified curing agent | 5 | EE |

continued

Table 1. Continued

| Adhesive | Generic Name | Class[a] | NCEL Code |
|---|---|---|---|
| Tracon "Trabond 2114" | epoxy/unspecified curing agent | 5 | FF |
| Tracon "Trabond 2122" | epoxy/unspecified curing agent | 5 | GG |
| Tracon "Trabond 2123" | epoxy/unspecified curing agent | 5 | HH |
| Tracon "Trabond 2126" | epoxy/unspecified curing agent | 5 | II |
| Tracon "Trabond 2135D" | epoxy/unspecified curing agent | 5 | JJ |
| Tracon "Trabond 2143D" | epoxy/unspecified curing agent | 5 | KK |
| VIP Vinyl Repair | polyvinyl chloride | 2 | LL |
| Weldwood Resorcinol | resorcinol/formaldehyde | 2 | MM |
| Weldwood Woodworker's Glue | resorcinol/formaldehyde | 2 | NN |
| 3C Quick Tack | acrylic | 2 | OO |
| 3C White Glue | methacrylic | 1 | PP |

[a]Classes are described in text under CLASSIFICATION OF ADHESIVES.

Table 2. Recommended Adhesives for Bonding Different Materials

| Substrate Material or Adherends | Adhesive | Tensile Strength (psi) |
|---|---|---|
| Steel-to-steel | Duro E-Pox-E (G) | 1,700 ± 30 |
| | Daubond polyester (O) | 2,000 ± 50 |
| | Hardman Kalex urethane (P) | 2,500 ± 50 |
| | Tracon "Trabond 2114" epoxy (FF) | 4,000 ± 75 |
| | Reziweld 1000 epoxy (BB) | 2,000 ± 50 |
| Wood-to-wood | Hardman Kalex Hi-Peel | 500 ± 10 |
| | Hardman regular set epoxy (Q) | 500 ± 10 |
| | Tracon "Trabond 2123" epoxy (HH) | 500 ± 10 |
| | Tracon "Trabond 2143D" epoxy (KK) | 550 ± 10 |
| Brass-to-brass | Daubond "Bondo" polyester (F) | 1,800 ± 20 |
| | Hardman "acrylic" (K) | 3,300 ± 100 |
| Aluminum-to-aluminum | Hardman "Water Clear Epoxy" (T) | 1,750 ± 50 |
| | Hardman acrylic (K) | 3,000 ± 100 |
| | Hughson-Lord Versilok accelerator #4 acrylic (V) | 2,700 ± 60 |
| | Hughson-Lord Versilok accelerator #5 acrylic (W) | 2,700 ± 60 |
| | Tracon "Trabond 2122" epoxy (GG) | 1,700 ± 50 |
| | Reziweld 1000 epoxy (BB) | 2,500 ± 100 |
| Steel-to-concrete | Daubond "Bondo" polyester (F) | 500 ± 10 |
| | Hardman fast setting epoxy (M) | 500 ± 10 |
| Steel-to-glass | Hughson-Lord Versilok accelerator #4 acrylic (V) | 1,200 ± 30 |
| | Reziweld 1000 epoxy (BB) | 1,250 ± 30 |
| Aluminum-to-glass | Hughson-Lord Versilok accelerator #4 acrylic (V) | 1,100 ± 20 |
| Aluminum-to-concrete | None recommended | |
| Titanium-to-steel | Hardman "very flexible" urethane (S) | 500 ± 10 |
| Titanium-to-concrete | Hardman epoxy (U) | 500 ± 10 |
| Brass-to-concrete | Hardman general purpose epoxy (N) | 500 ± 10 |
| | Hardman "Water Clear Epoxy" (T) | 570 ± 10 |
| | Hardman fast setting epoxy (M) | 510 ± 10 |

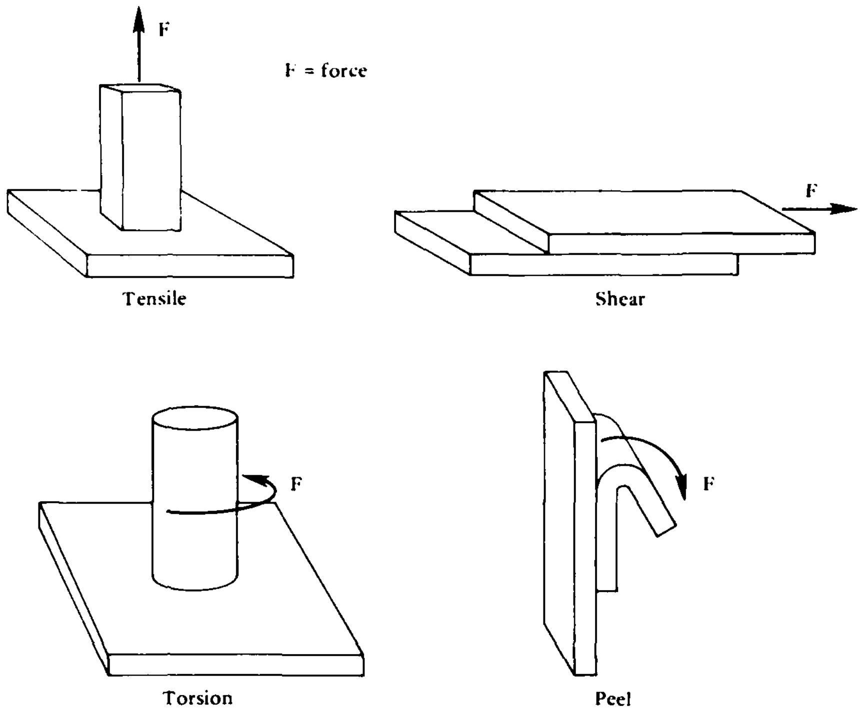



Figure 1. Types of destructive laboratory testing of adhesive strength.

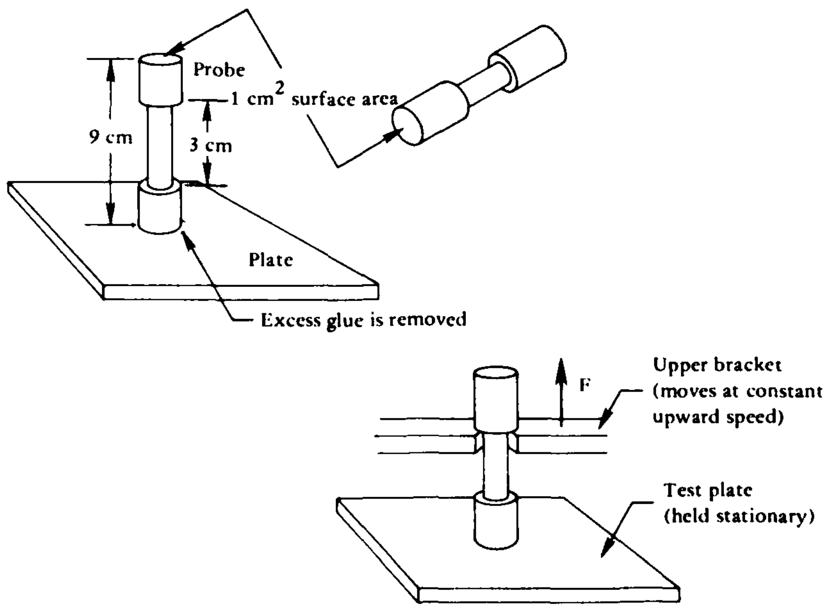



Figure 2. Tensile test of adhesive.

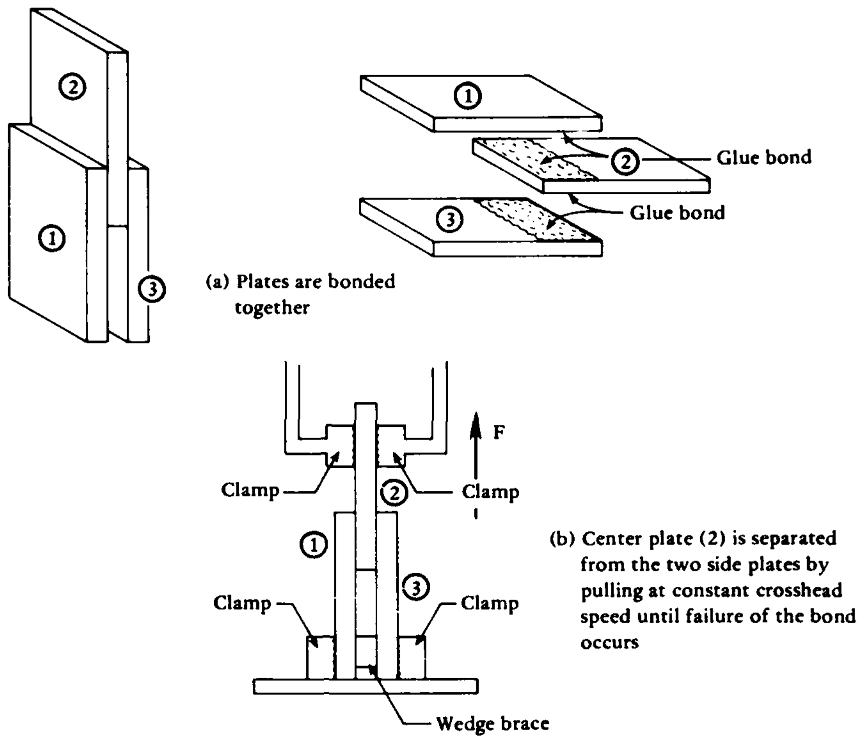



Figure 3. Double-lap tensile shear test of adhesive.

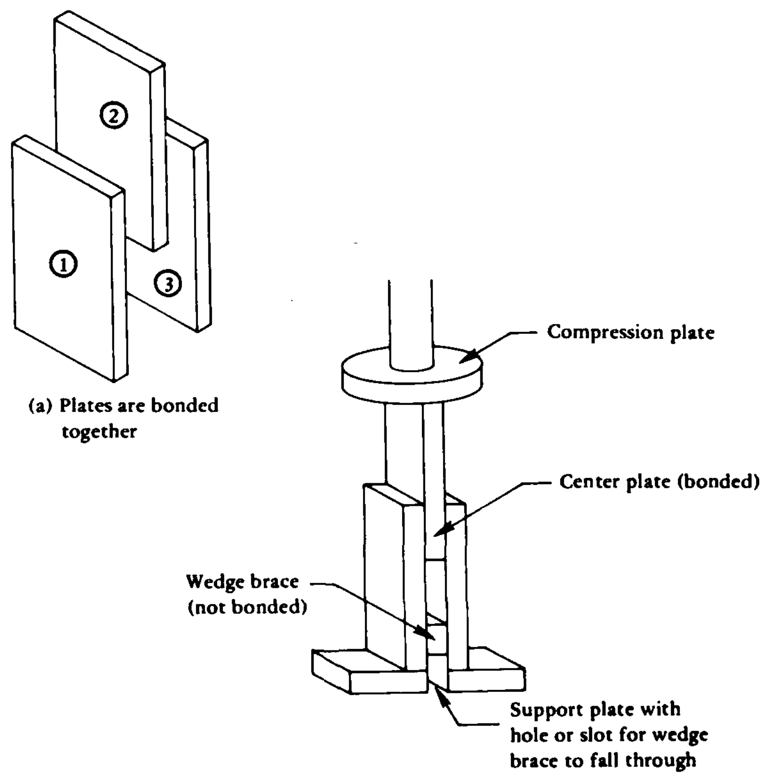



Figure 4. Double-lap compressive shear test of adhesive.

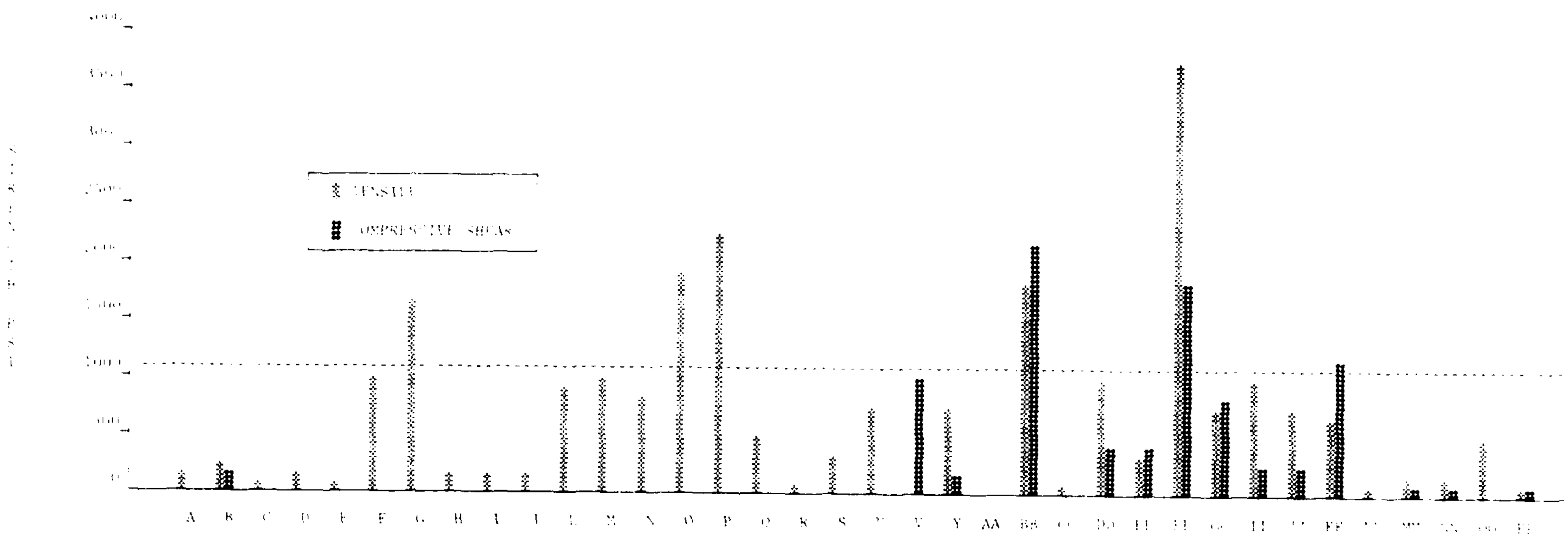


Figure 5. Thirty-six different adhesives bonding steel-to-steel.

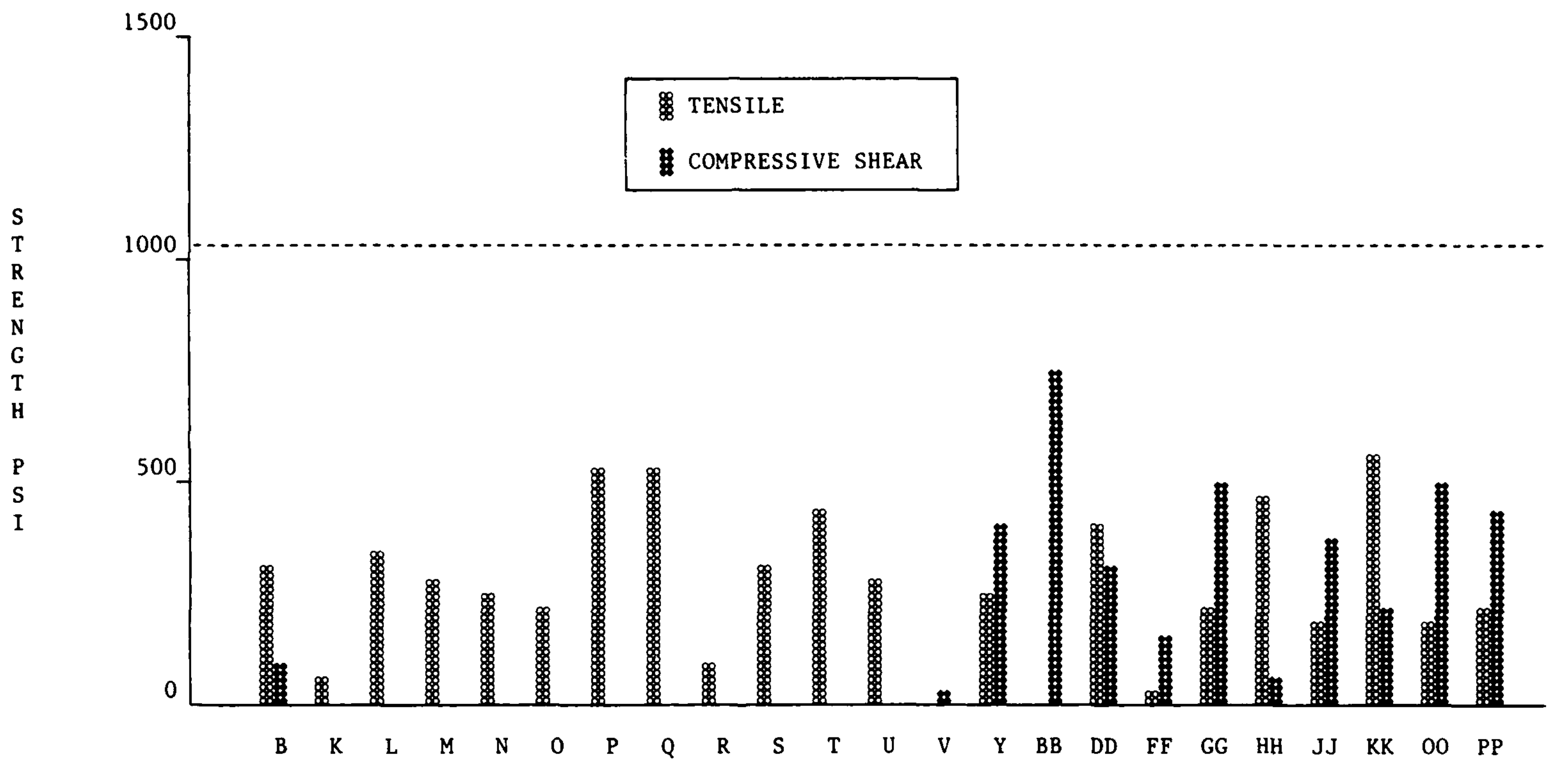



Figure 6. Twenty-three different adhesives bonding wood-to-wood.

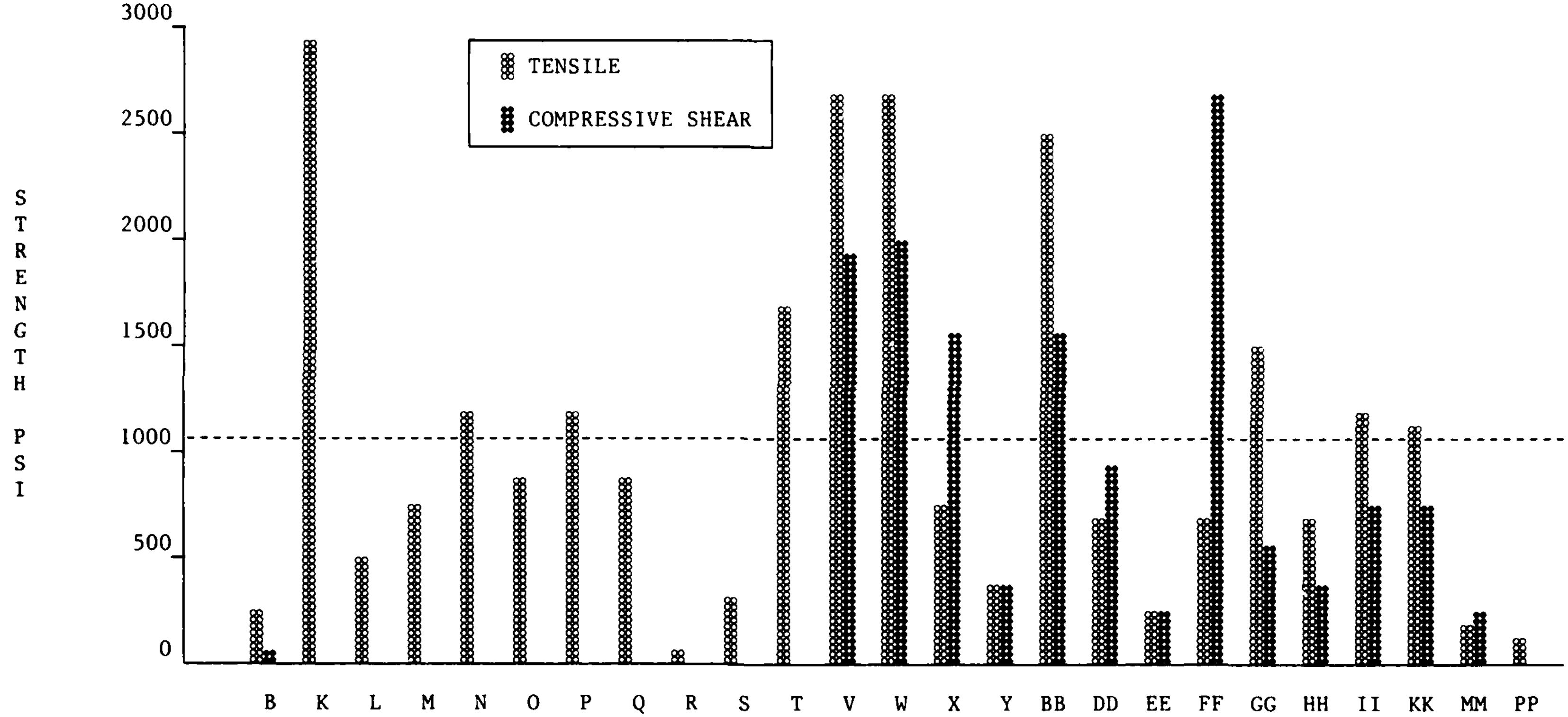



**Figure 7.** Twenty-five different adhesives bonding aluminum-to-aluminum.

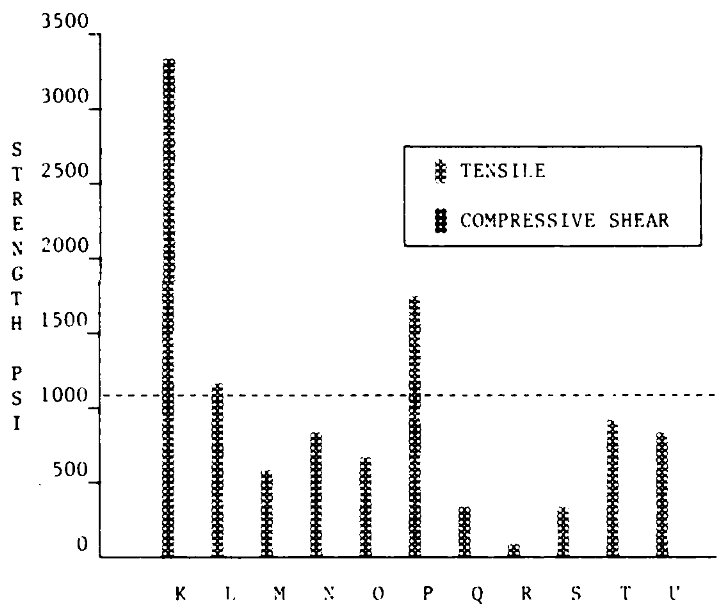



**Figure 8. Eleven different adhesives bonding brass-to-brass.**

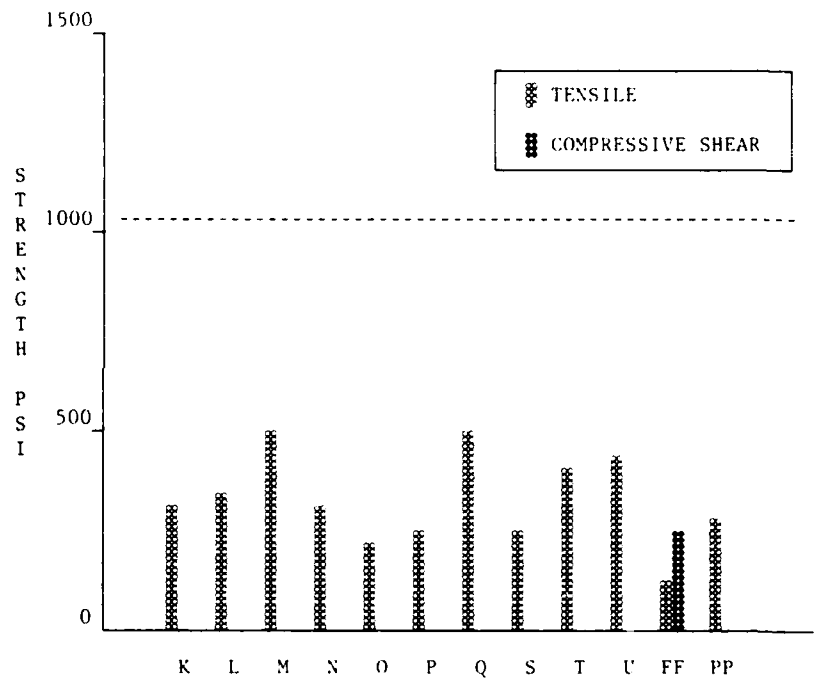



**Figure 9. Twelve different adhesives bonding steel-to-concrete.**

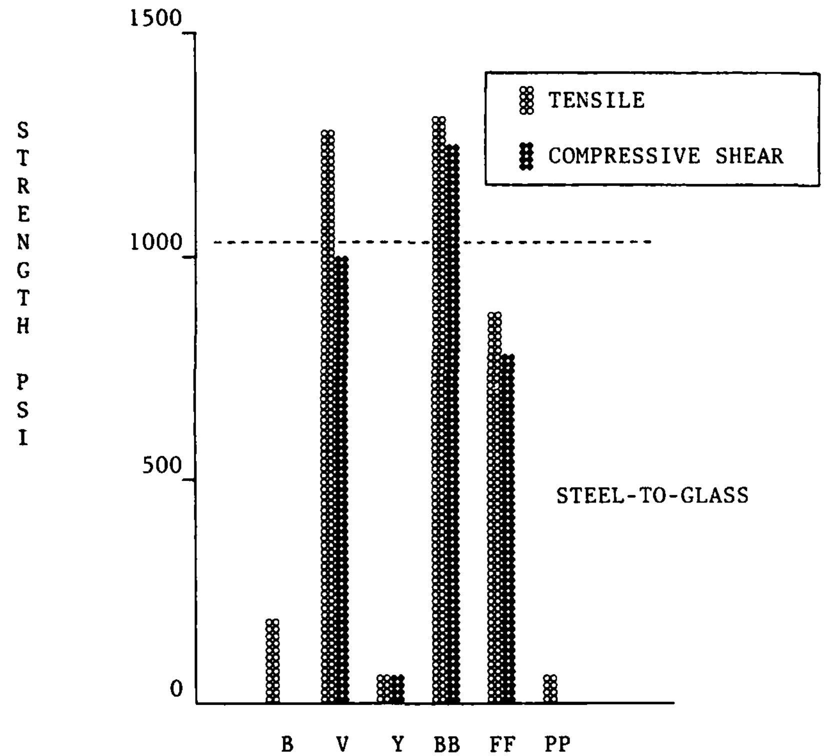



**Figure 10.** **Six different adhesives bonding steel-to-glass.**

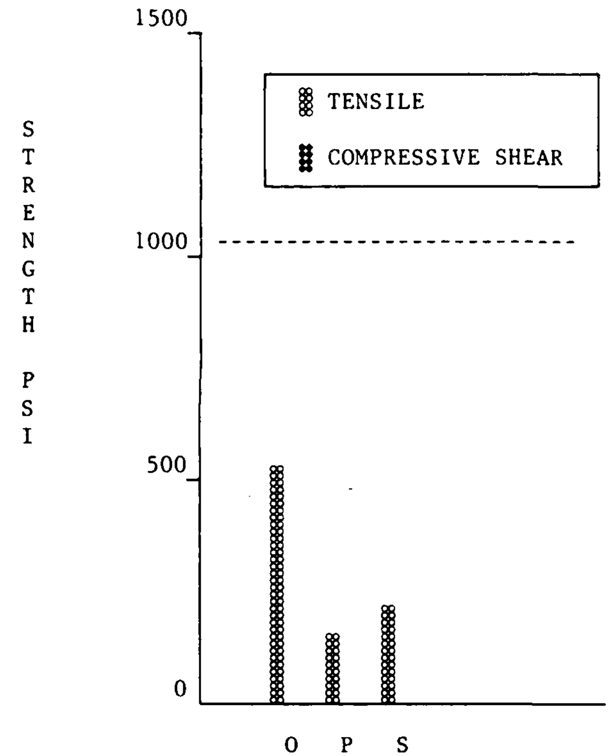



**Figure 11.** **Three different adhesives bonding aluminum-to-concrete.**

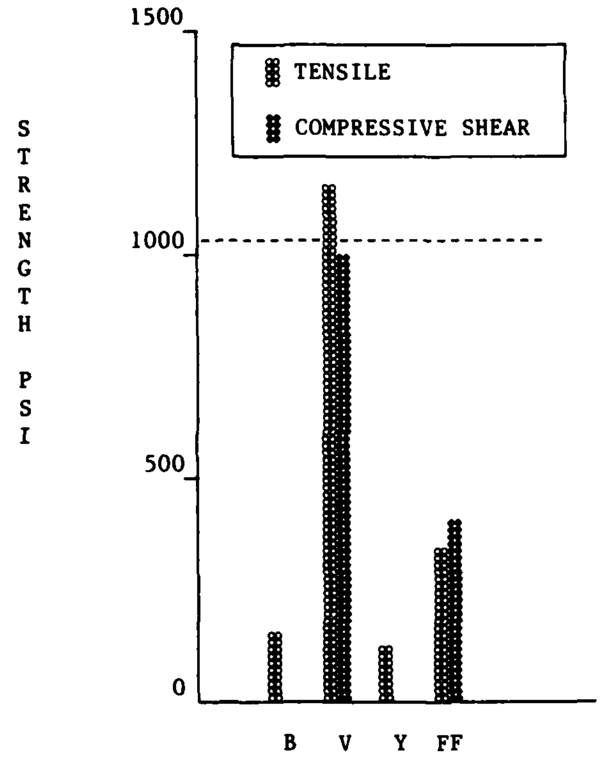



Figure 12. Four different adhesives bonding aluminum-to-glass.

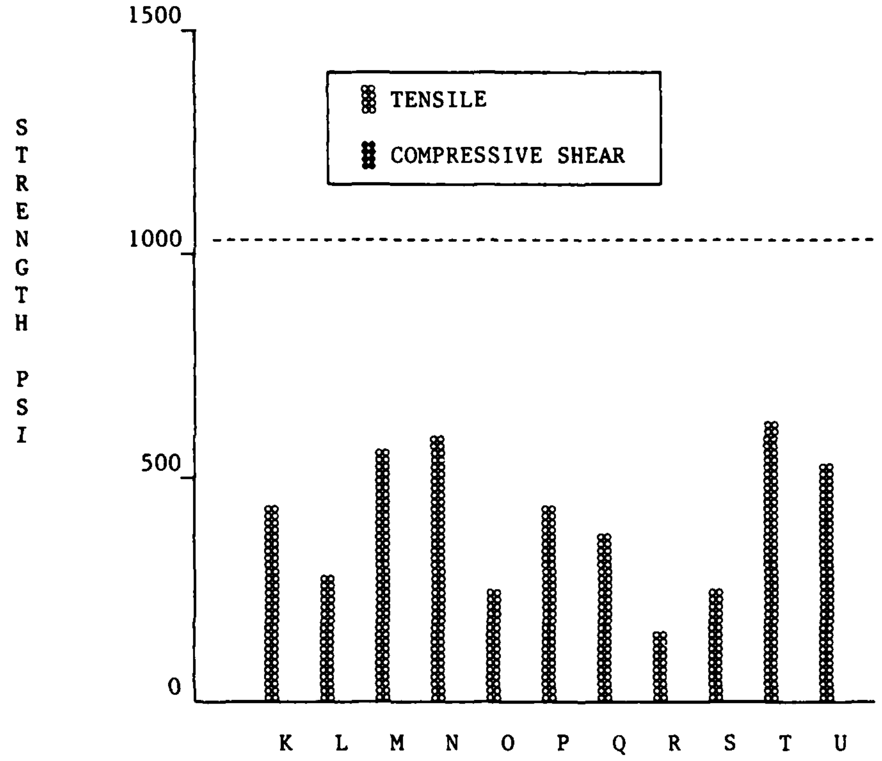



Figure 13. Eleven different adhesives bonding brass-to-concrete.

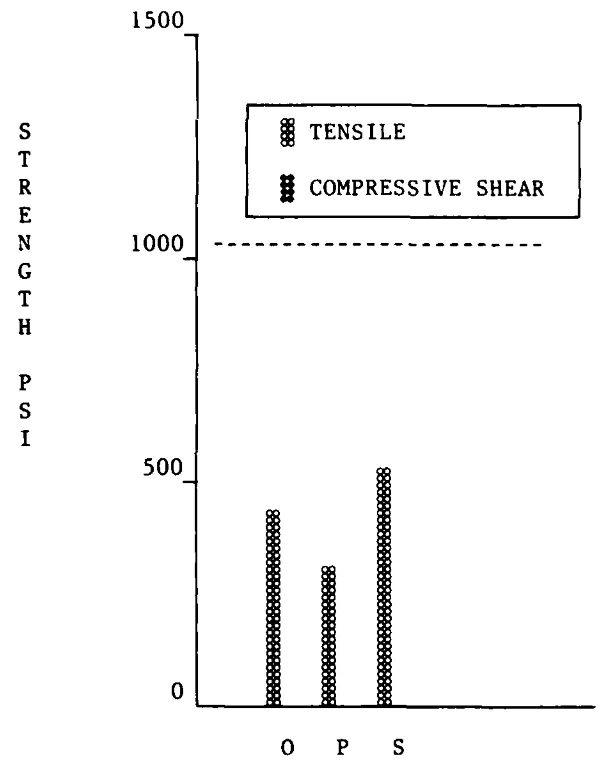



**Figure 14.** **Three different adhesives bonding titanium-to-steel.**

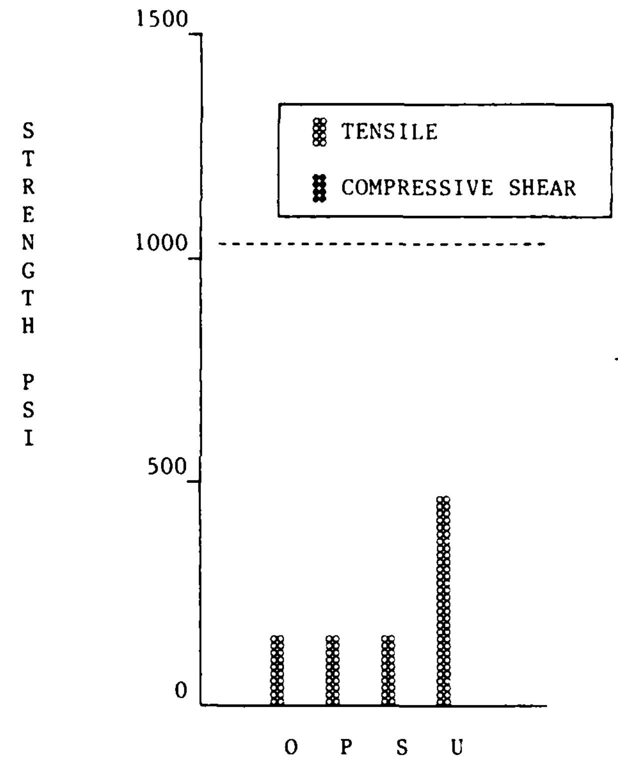
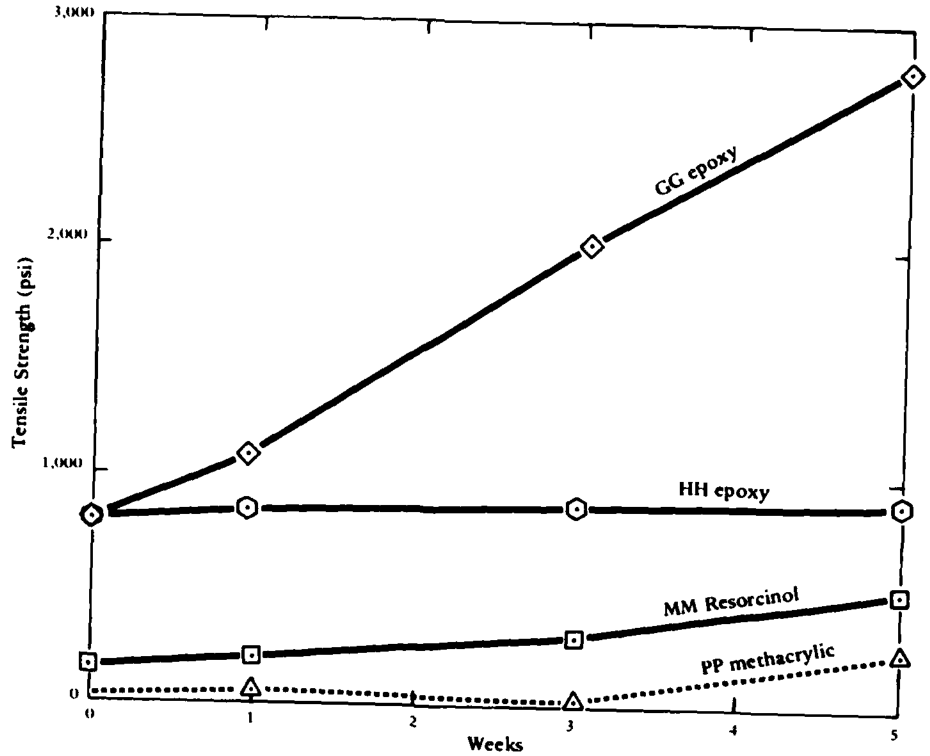
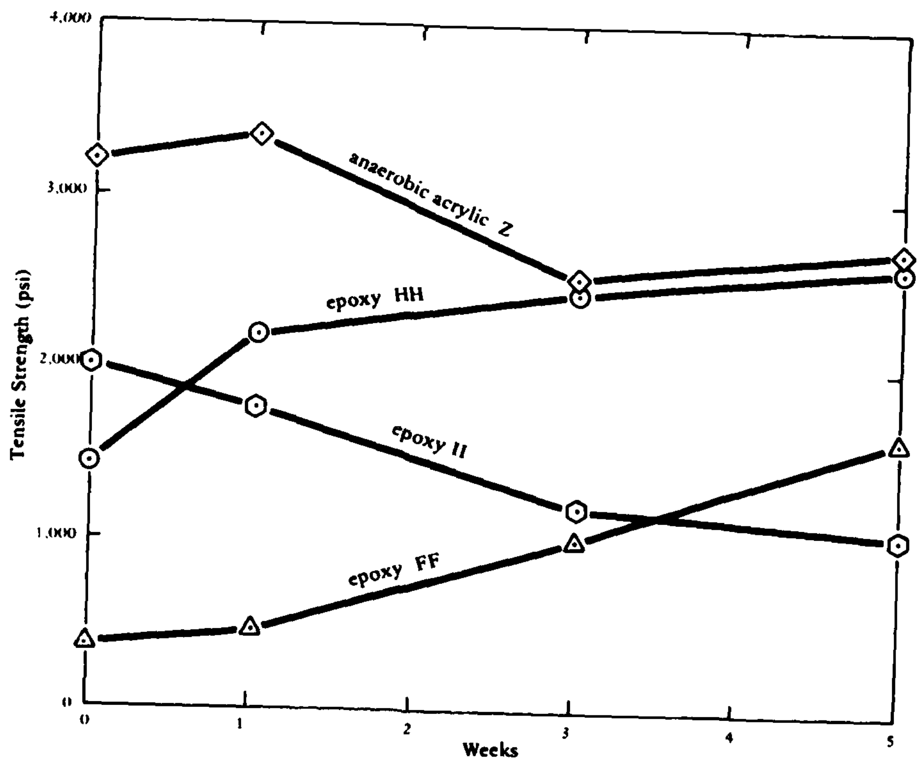



**Figure 15.** **Four different adhesives bonding titanium-to-concrete.**

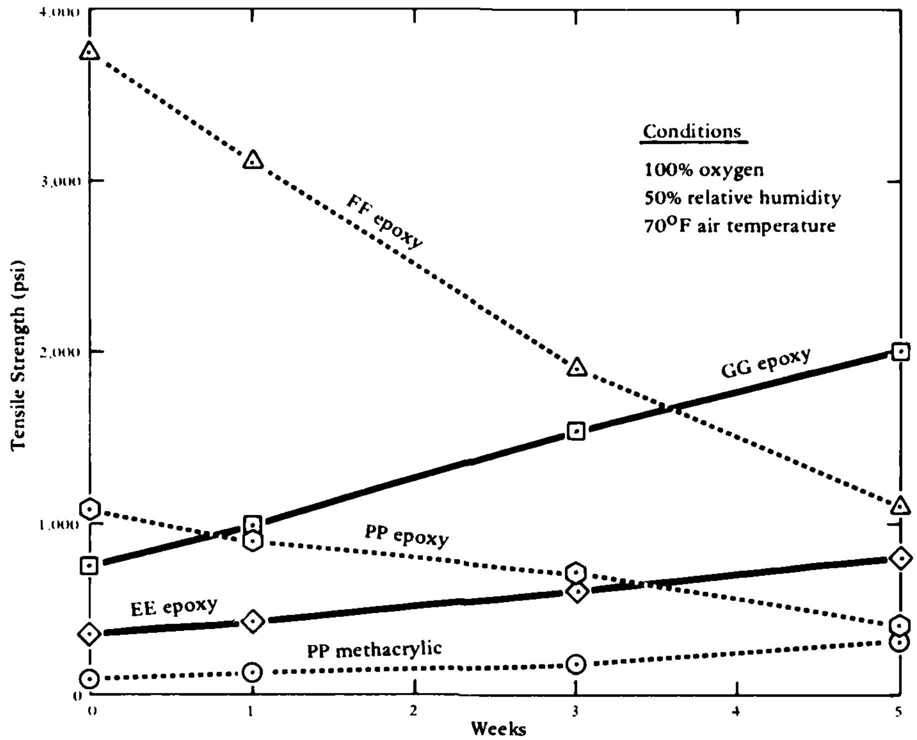



(a) Steel-to-steel.

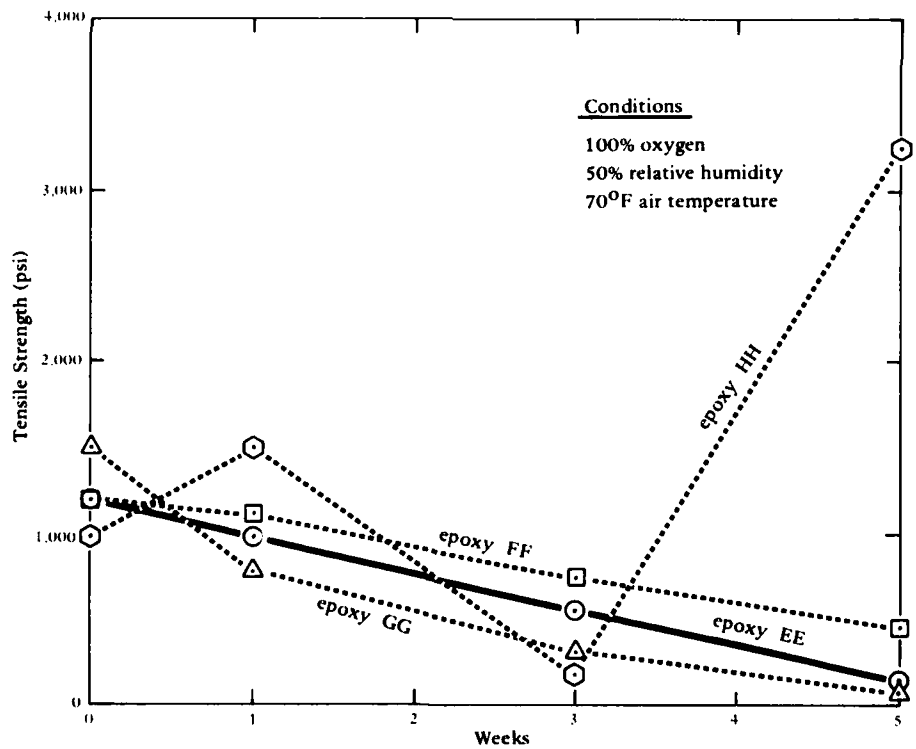



(b) Aluminum-to-aluminum.

Figure 16. Effects of seawater immersion (70°F) on adhesives.

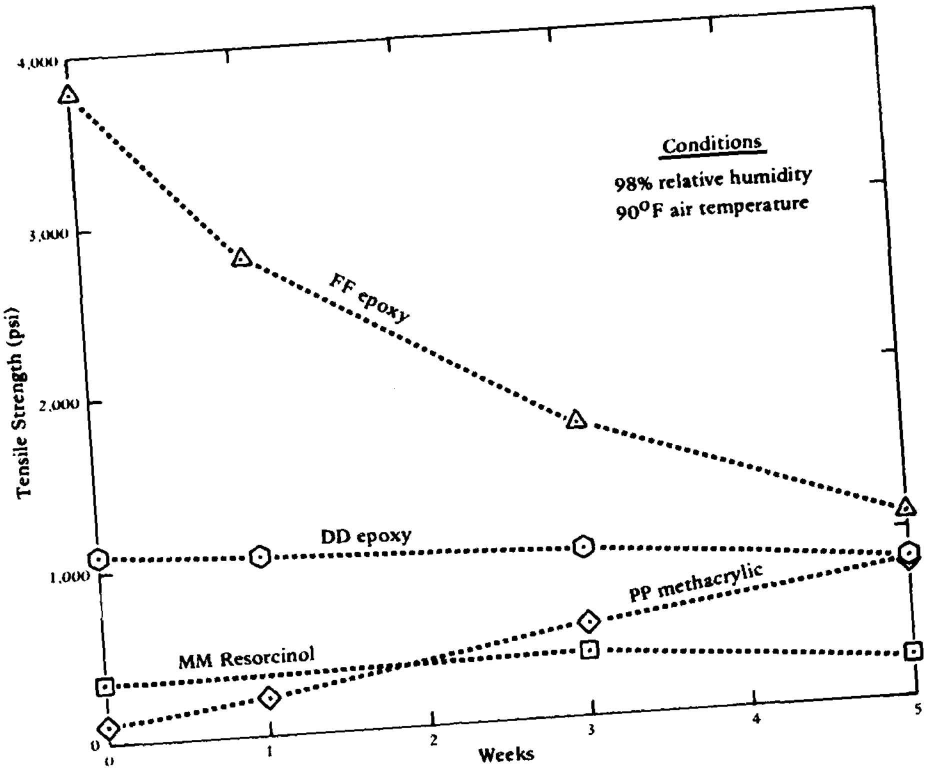



(a) Steel-to-steel.

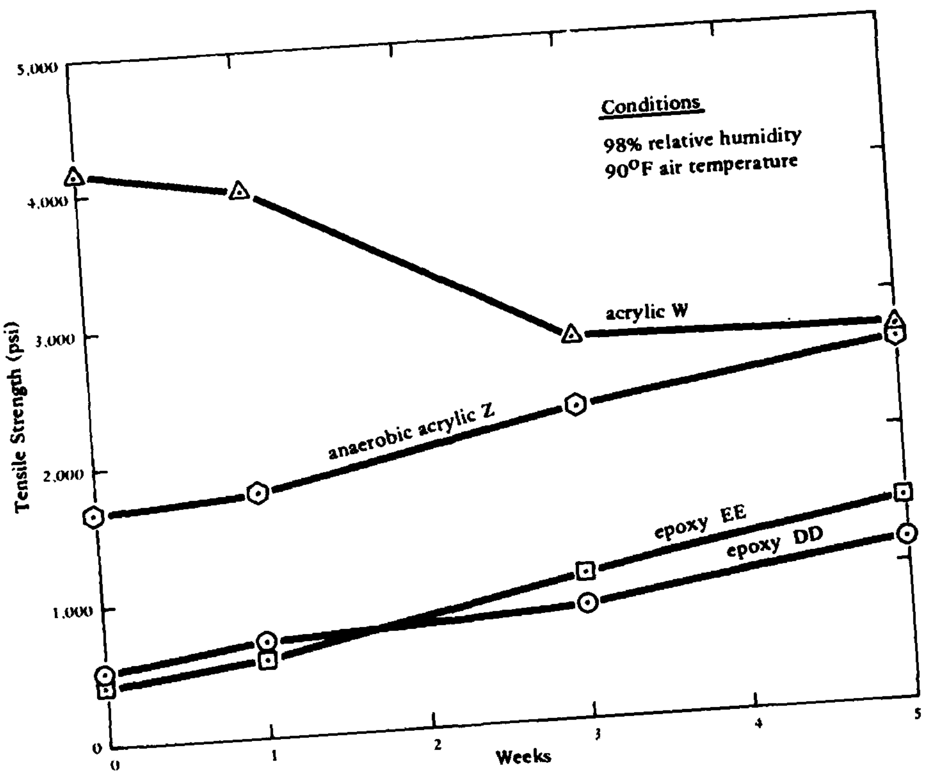



(b) Aluminum-to-aluminum.

Figure 17. Effects of oxygen on adhesives.

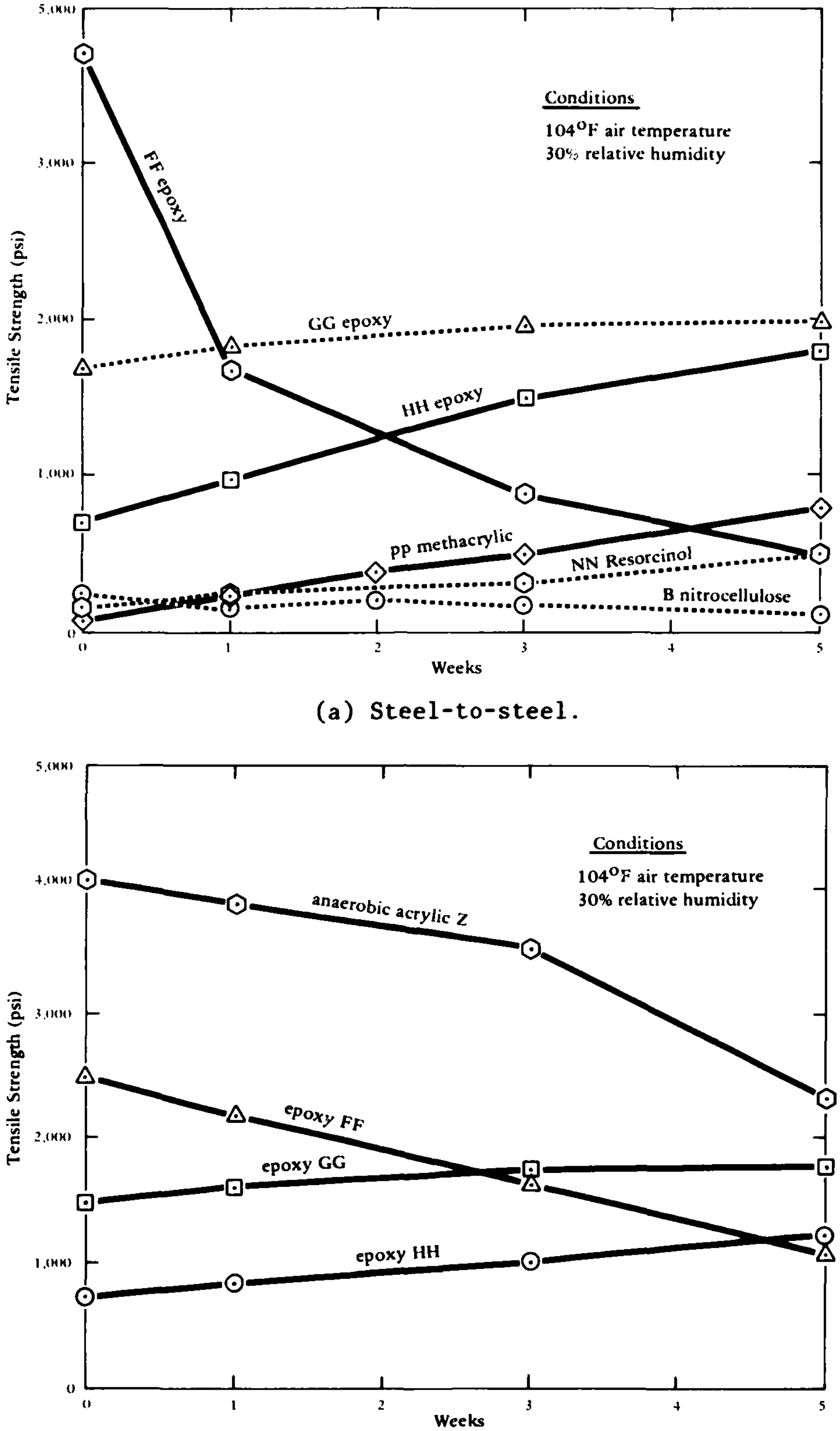



(a) Steel-to-steel.




(b) Aluminum-to-aluminum.

Figure 18. Effects of heat and humidity on adhesives.

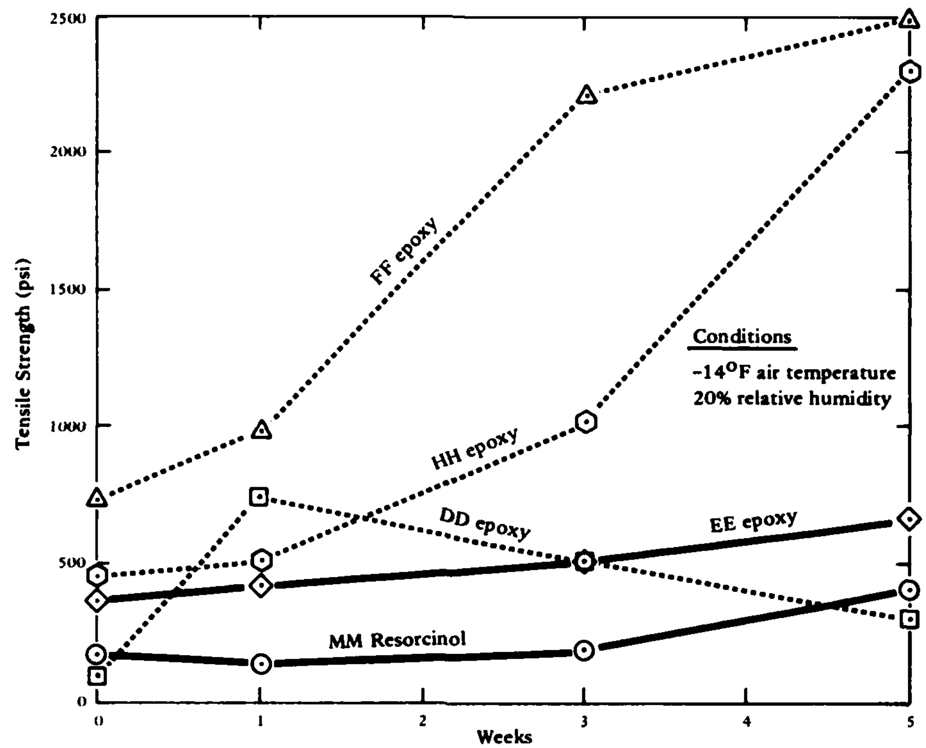



(a) Steel-to-steel.

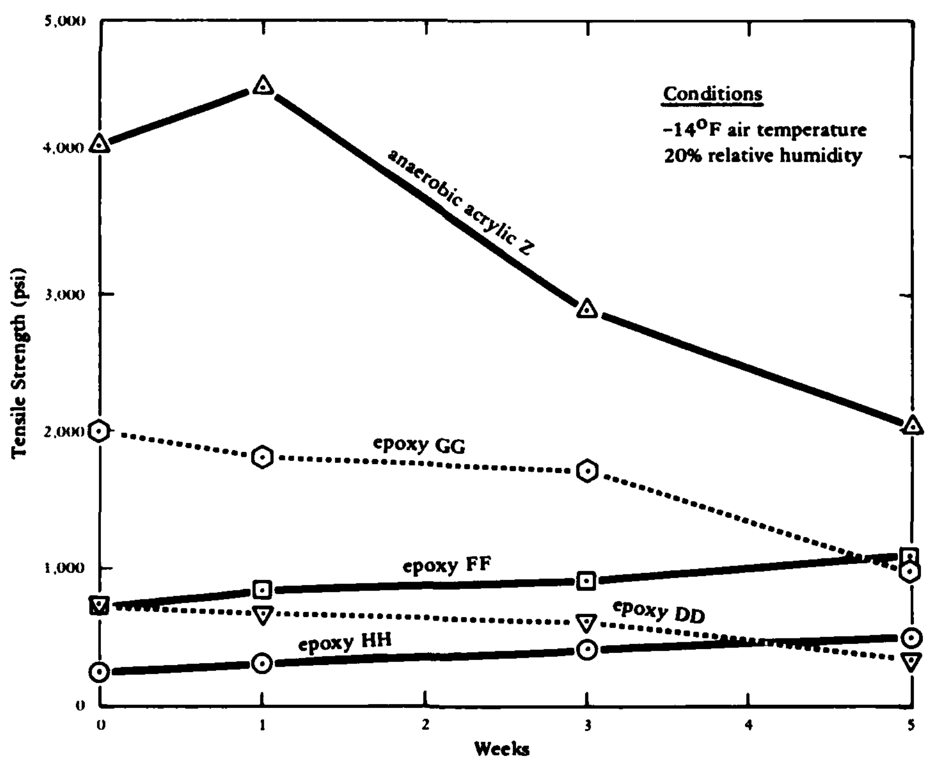


(b) Aluminum-to-aluminum.

Figure 19. Effects of dry heat on adhesives.




(a) Steel-to-steel.




(b) Aluminum-to-aluminum.

Figure 20. Effects of cold temperatures on adhesives.

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